

TQC 2D Mechanical Design. Part 1

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A coil supporting structure for the TQC quadrupole consists of two components: the collars and the spacer-yoke-skin assembly.

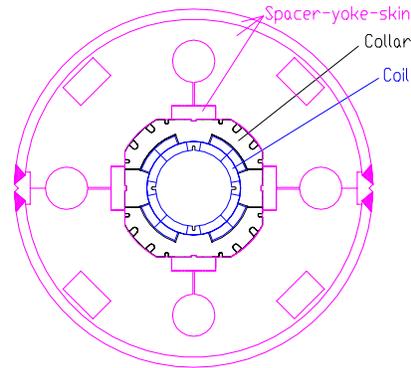


Fig.1 TQC components

The first component, the collars, due to flexibility, may form coil boundaries and define internal coil stress distribution.



Fig.2 a) cross-section of the coil straight section b) cross-section of the transition between straight section and coil end

The second component, the spacer-yoke-skin, delivers required forces for shaping of boundaries of the collared coil.

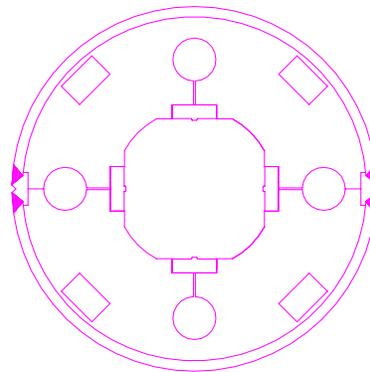


Fig. 3 Spacer-yoke-skin assembly

In this note only collared coil structure will be analyzed.

Collared Block.

The collared coil FE models are shown on Fig 4. The model is 2mm thick. Coil material properties listed in Table 1. Table 2 shows results of ANSYS calculation for stand-alone collars in two cross-sections of the magnet: at the magnet straight part and at the transition area. There are two different collars in these cases: collars with pole and rounded collars (see Fig 4). Note, the goal for stress in Nb3Sn coil is <150MPa.

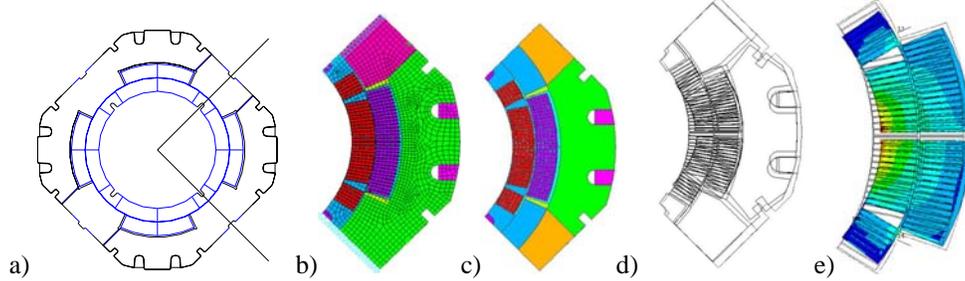


Fig. 4 a) model; b) model with pole collar; c) model with round collar; d) collared block deformation under LF; e) distribution of coil stress under LF

Table 1 Coil properties.

Parameter	Unit	Nb3Sn Coil	
		300 K	2 K
Ex – Azimuthal direction	GPa	44	44
Ey – Radial direction	GPa	44	55
α_x	E-3	2.6	
α_y	E-3	3.5	

Table2. Stand-alone collars

Collar material	mp shim, mm	Scoil max, MPa	Coil straight section			Coil end near transition region		
			300K	2K	B=233Tm	300K	2K	B=233Tm
SS	0.01	Scoil max, MPa	49	53	314	53	66	343
		dRcollar-mp, mm	0.030	-0.226	-0.058	0.025	-0.225	-0.002
		dRcollar-pole, mm	0.029	-0.131	-0.079	0.035	-0.144	-0.101
		Fpole1	-437	-85	0	-370	-200	0
SS	0.15	Scoil max, MPa	74	76	327	80	94	354
		dRcollar-mp, mm	0.045	-0.212	-0.060	0.053	-0.208	-0.005
		dRcollar-pole, mm	0.044	-0.116	-0.078	0.038	-0.132	-0.100
		Fpole1	-647	-289	0	-608	-284	0
AL	0.1	Scoil max, MPa	30	88	391	30	106	434
		dRcollar-mp, mm	0.039	-0.307	0.007	0.045	-0.290	0.095
		dRcollar-pole, mm	0.055	-0.255	-0.093	0.035	-0.181	-0.085
		Fpole1	-277	-1000	0	-217	-421	0
AL	0.15	Scoil max, MPa	46	103	400	45	123	443
		dRcollar-mp, mm	0.059	-0.288	0.003	0.068	-0.268	0.091
		dRcollar-pole, mm	0.058	-0.161	-0.065	0.053	-0.164	-0.084
		Fpole1	-406	-1167	0	-406	-1167	0

Collars are very soft for given force level $F_x=1.44\text{MN/m}$, $F_y=-2.19\text{MN/m}$ on 1/8 at $B_{grad}=233\text{T/m}$ in order to keep coil peak stress on the level of 150MPa. Even with allowable pole separation, the coil peak stress is >310MPa for SS collars and >390MPa for AL collars. Max collar deformation at parting plane under LF is >0.150mm and >0.285mm for SS and AL collars respectively.

Therefore, the collars need outside support to prevent big coil bending.

Assume the best supporting point for the collars will be near the coil parting plane, where LF are summarized (Fig 5a). The supporting point may extend to supporting line (for 2D model, Fig 5 b, and c).

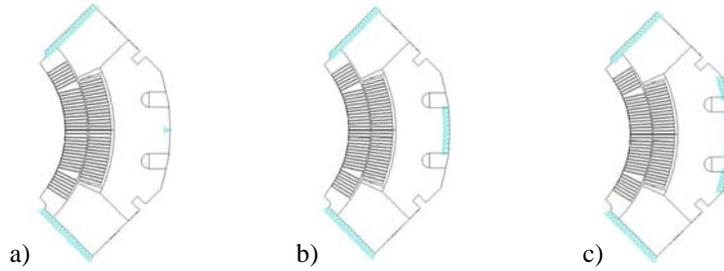


Fig. 5 Variants for collar support.

Let's find out optimal deformed shape of collared coil assembly at 2K with acting LF (Fig 5a). Stress in Nb3Sn coil will be a target function. Coil midplane shim, radial collar deformation dR, collar's material will be design parameters. Partial pole separation will be accepted. Fpole = 0N means 100% separation. Fmp is collar's reaction force at coil midplane. Results are listed in Table 3.

Table 3. Results for block supported at one midplane point on OR at coil straight section (a-case on Fig.5):

Collar material	mp shim, mm	dRmp, mm	RF, N	Scoil max, MPa	Fpole1(up)	Fpole1(d)	Fpole2(up)	Fpole2(d)	Fmp(28)	
SS	0.01	0.25	5235	137	0	0	0	0		
		0.275	5890	121	0	0	0	0		
		0.3	6590	127	0	0	0	0	-4897	
		0.325	6769	129	0	0	0	0	-5	-4888
		0.35	7264	142	-24	-23	-285	-286	-5187	
SS	0.15	0.25	5172	150	0	0	0	0		
		0.275	5835	133	0	0	0	0		
		0.3	6569	122	0	0	-154	-154	-5082	
		0.325	7368	139	-35	-33	-381	-382	-5308	
		0.35	8117	157	-218	-215	-647	-649	-5718	
AL	0.15	0.3	3724	198	0	0	0	0		
		0.35	4346	170	0	0	-61	-61	-5093	
		0.4	5003	144	-30	-29	-126	-126	-5137	
		0.45	6130	136	-528	-527	-130	-130	-5530	
		0.5	7281	163	-1045	-1043	-156	-156	-5965	

Results show: with one contact point, the SS collars should be deformed inside by 0.325-0.35mm to reach optimal coil stress ~150MPa. Deformation is 0.425mm for AL collars. Both cases have small reaction forces at the pole of the first layer. Reaction force or force needed for block deformation is 7400N for SS and 5500N for AL variants. Both cases delivered ~5300N to the coils parting plane.

Table 4 presents result of collared block deformation along the line (Fig 5c).

Table 4. Contact extended from point to line at coil straight section (c-case on Fig. 5).

Collar material	mp shim, mm	dRmp, mm	RF, N	Scoil max, MPa	Fpole1(up)	Fpole1(d)	Fpole2(up)	Fpole2(d)	Fmp(28)
SS	0.01	0.3	7849	146	-1	0	-622	-622	-5621
		0.325	8897	154	-212	-207	-1076	-1079	-6266
		0.35	10104	167	-608	-602	-1448	-1452	-7003
SS	0.15	0.275	8075	155	-13	-13	-756	-757	-5790
		0.3	9159	165	-262	-257	-1197	-1200	-6456
		0.325	10374	178	-669	-663	-1562	-1566	-7198
AL	0.15	0.3	4777	191	0	0	-185	-185	-5275
		0.35	6438	180	-458	-454	-339	-342	-5806
		0.4	8639	182	-1265	-1260	-544	-548	-6704
		0.45	10724	204	-2036	-2031	-767	-771	-7599

Results show: with extension of deformed line on the collar outside surface to 35% (max available for present design), required deformation decreased to 0.3mm for SS and 0.35mm for AL collars. Coil stress increased to 155MPa for SS and 180MPa for AL collars. Moreover, forces needed for block deformation increased to 9100N for SS and 6400N for AL variants. Both cases delivered ~6000N to the coil's parting plane.

Results for intermediate case show in Tables 5(straight section) and 6(transition area). Only 13% of collar OR is deformed near coil parting plane, length of the contact line limited by keyways (Fig.5b). Two cases were added to the table: room temperature stage at 300K and after cooling down to 2K.

Table 5. Coil straight section.

Collar material	mp shim, mm	dRmp, mm	RF, N	Scoil max, MPa	Fpole1(up)	Fpole1(d)	Fpole2(up)	Fpole2(d)	Fmp	
SS	0.01	0.35	12806	382	-5407	-5400	-3649	-3654	-8360	300K
			5001	147	-1796	-1850	-1613	-1562	-3190	2K
			8313	168	-286	-294	-839	-828	-5976	B
SS	0.01	0.325	12000	359	-5075	-5069	-3427	-3432	-7852	300K
			4097	120	-1434	-1481	-1369	-1323	-2632	2K
			7472	147	-45	-14	-515	-538	-5455	B
SS	0.15	0.3	12161	361	-5116	-5110	-3495	-3500	-7970	300K
			4144	124	-1501	-1547	-1567	-1522	-2929	2K
			7075	144	-67	-37	-689	-708	-5675	B
AL	0.1	0.375	9283	317	-5134	-5129	-1641	-1645	-5882	300K
			2025	122	-1908	-1952	-551	-517	-2295	2K
			5438	125	-44	-45	-70	-67	-5070	B
AL	0.15	0.35	9363	318	-5164	-5160	-1671	-1675	-5962	300K
			1893	127	-1985	-2033	-754	-715	-2611	2K
			5168	143	-126	-135	-221	-211	-5346	B

As seen from Table 5, SS collars should be deformed >0.3mm and AL one by >0.35mm to reach optimal coil peak stress ~140-150MPa at 2K. Forces needed for block deformation are >7600N for SS and >5200 for AL variants. One can conclude, the AL collars compare to SS one required less force for block deformation and therefore thinner skin but collar deformation will be bigger.

Table 6. Coil section at transition region.

Collar material	mp shim, mm	dRmp, mm	RF, N	Scoil max, MPa	Fpole1(up)	Fpole1(d)	Fpole2(up)	Fpole2(d)	Fmp	
SS	0.01	0.35	4403	154	-1894	-1948	-978	-928	-2689	2K
			7943	160	-375	-400	-415	-390	-5620	B
SS	0.01	0.325	3585	128	-1537	-1586	-801	-757	-2195	2K
			7126	148	-84	-70	-165	-180	-5131	B
SS	0.15	0.3	3571	135	-1627	-1672	-1038	-996	-2541	2K
			7186	147	-113	-109	-297	-300	-5315	B
AL	0.1	0.4	2967	154	-1890	-1937	-1153	-1110	-2880	2K
			6349	156	-172	-196	-495	-471	-5572	B
AL	0.15	0.35	2344	139	-1672	-1717	-1318	-1276	-2892	2K
			5573	167	0	0	-568	-570	-5576	B
		0.375	2970	161	-1969	-2017	-1373	-1329	-3197	2K
		6269	155	-245	-273	-688	-661	-5876	B	
		0.4	3575	182	-2267	-2318	-1422	-1375	-3500	2K
			6990	168	-550	-580	-776	-746	-6198	B

Results also show, it should be different dR for different working stages to keep Scoil<150MPa.

Tables 7, 8, 9, and 10 show optimization results (Fig 5b) for 3 working conditions of the magnet: after assembly at 300K, after cool down to 2K, and at Bmax. Block deformation force RF and coil peak stress Scoil max as functions of collar's dR are presented for SS and AL collars and different coil mid-plane shims.

Table 7. Optimization results for coil straight section and SS collars.

Coll. Mat.	m-p shim, mm	dR, mm	Scoil max, MPa	RF, N	Cond.
SS	0.01	0	54	1379	300K
		0.05	101	3480	
		0.1	146	5354	
dR change is 0.1-0.35=-0.25mm					
		0.3	93	3174	2K
		0.325	120	4097	
		0.35	147	5001	
dR change is 0.35-0.325=0.025mm					
		0.3	130	6796	Bmax
		0.325	147	7472	
		0.35	168	8313	
SS	0.15	0	81	2073	300K
		0.05	130	4216	
		0.1	174	6212	
dR change is 0.05-0.325=-0.275mm					
		0.3	124	4144	2K
		0.325	150	5173	
		0.35	177	6077	
dR change is 0.3-0.325=-0.025mm					
		0.3	144	7589	Bmax
		0.325	166	8476	
		0.35	188	9400	

To keep Scoil max < 150MPa the SS collars need to be deformed radially at coil's parting plane, and at magnet straight section:

- with 0.1mm coil m-p shim
 - <0.100mm at 300K (RF<5300N)
 - <0.350mm at 2K (RF<5000N)
 - =0.325mm at Bmax (RF<7400N)
- with 0.15mm coil m-p shim
 - <0.075mm at 300K (RF<4500N)
 - <0.325mm at 2K (RF<5200N)
 - =0.300mm at Bmax (RF<7600N)

Moreover, skin stress at 300K should be < or = 250MPa.

Table 8. Optimization results for coil straight section and AL collars.

Coll. Mat.	m-p shim, mm	dR, mm	Scoil max, MPa	RF, N	Cond.
AL	0.1	0	53	1274	300K
		0.05	81	2194	
		0.1	117	3317	
		0.15	152	4430	
dR change is 0.15-0.4=-0.25mm					
		0.375	122	2025	2K
		0.4	143	2710	
		0.425	164	3378	
dR change is 0.425-0.4=0.25mm					
		0.375	125	5438	Bmax
		0.4	136	6143	
		0.425	152	6882	
AL	0.15	0	69	1554	300K
		0.05	104	2723	
		0.1	140	3855	
dR change is 0.1-0.375=-0.275mm					
		0.3	86	382	2K
		0.35	127	1893	
		0.375	149	2603	
		0.4	170	3288	
dR change is 0.4-0.375=0.25mm					
		0.3	173	4323	Bmax
		0.35	143	5168	
		0.4	149	6721	

To keep Scoil max<150MPa the AL collars need to be deformed at magnet straight section:

0.1mm m-p shim

- <0.150mm at 300K (RF<4400N)
- <0.400mm at 2K (RF<2700N)
- =0.425mm at Bmax (RF<6900N)

0.15mm m-p shim

- <0.100mm at 300K (RF<3800N)
- <0.375mm at 2K (RF<2600N)
- =0.400mm at Bmax (RF<6700N)

Table 9. Optimization results for coil transition area and SS collars.

Coll. Mat.	m-p shim	dR, mm	Scoil max, MPa	RF, N	Cond.
SS	0.01	0.1	142	4741	300K
		0.125	163	5558	
dR change is 0.1-0.35=-0.25mm					
		0.325	128	3585	2K
		0.35	154	4403	
dR change is 0.325-0.35=-0.025mm					
		0.325	148	7126	Bmax
		0.35	160	7943	
SS	0.15	0.075	150	4648	300K
		0.1	171	5476	
dR change is 0.075-0.325=-0.25mm					
		0.3	135	3571	2K
		0.325	159	4472	
dR change is 0.3-0.32=-0.02mm					
		0.3	147	7186	Bmax
		0.325	160	8109	

To keep Scoil max<150MPa the SS collars need to be deformed at magnet transition area:

0.1mm m-p shim

<0.110mm at 300K (RF<5000N)
 <0.350mm at 2K (RF<4400N)
 =0.325mm at Bmax (RF<7100N)

0.15mm m-p shim

<0.075mm at 300K (RF<4600N)
 <0.315mm at 2K (RF<4000N)
 =0.300mm at Bmax (RF<7200N)

Table 10. Optimization results for coil transition area and AL collars.

Coll. Mat.	m-p shim	dR, mm	Scoil max, MPa	RF, N	Cond.
AL	0.1	0.125	134	3655	300K
		0.15	152	4160	
dR change is 0.15-0.4=-0.25mm					
		0.375	133	2364	2K
		0.4	154	2967	
		0.425	175	3555	
dR change is 0.375-0.4=-0.025mm					
		0.375	148	5713	Bmax
		0.4	156	6349	
		0.425	169	7057	
AL	0.15	0.1	140	3713	300K
		0.125	158	4221	
dR change is 0.12-0.37=-0.25mm					
		0.35	139	2344	2K
		0.375	161	2970	
		0.4	182	3575	
dR change is 0.375-0.37=-0.005mm					
		0.35	167	5573	Bmax
		0.375	155	6269	
		0.4	168	6990	

To keep Scoil max<150MPa the AL collars need to be deformed at magnet transition area:

0.1mm m-p shim

<0.150mm at 300K (RF<4100N)
 <0.400mm at 2K (RF<2900N)
 =0.425mm at Bmax (RF<5700N)

0.15mm m-p shim

<0.110mm at 300K (RF<4000N)
 <0.360mm at 2K (RF<2600N)
 =0.75mm at Bmax (RF<6300N)